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Spectral Response of Architecturally Different Wheat Canopies

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The spectral response of two architecturally different spring wheat canopies having similar single leaf reflectance, green leaf area index (GLAI), and total dry phytomass, was measured throughout a growing season. Experimental results and supporting model calculations showed that the more planophile canopy had a higher spectral reflectance (measured at nadir) than the erectophile canopy. During the period of peak GLAI, the ratio of near-infrared to red reflectances (IR/red) for the erectophile canopy was about 30% higher than for the planophile canopy. The perpendicular vegetation index (PVI), however, was about 30% higher for the planophile canopy than for the erectophile canopy. When ground measured reflectances were transformed to radiances exiting the top of either a clear or a turbid atmosphere, the differences between the erectophile and the planophile canopies remained for the PVI but were obscured for the IR/red ratio. The results demonstrate the importance of architectural effects on the spectral response of canopies, and the interpretation of that response for estimating GLAI and dry phytomass by use of vegetation indices.

Introduction

The architecture of a plant canopy determines the directions that radiation will be reflected from plant surfaces. The vertical arrangement of leaves in an erectophile canopy generally scatters more radiation into lower leaf layers than the more horizontal arrangement of a planophile canopy. Thus, the amount of radiation received by a radiometer at a particular view angle may vary considerably for geometrically different canopies. Even at a constant view angle, sun angle changes cause variations in spectral response from different architectures (Pinter et al., 1985).

Vegetation indices are used to discriminate vegetation amounts and condition (e.g., Aase and Siddoway, 1981; Ahlrichs and Bauer, 1983; Asrar et al., 1985). Two general classes of vegetation indices have been developed: ratios (Tucker, 1979; Perry and Lautenschlager, 1984), and orthogonal transformations (Kauth and Thomas, 1976; Richardson and Wiegand, 1977; Jackson, 1983). Of the two classes, the ratio of spectral response in the near-infrared and the red bands (IR/red), and the perpendicular vegetation index (PVI) of Richardson and Wiegand (1977) are commonly used. The nonlambertian properties of plant canopies caused by architecture also alter the magnitude of these indices, thus complicating the development of relationships between plant properties such as green leaf area index and the spectral indices.

Differences in spectral response of canopies due to architecture can be anticipated by use of canopy reflectance models (e.g., Suits, 1972; Verhoef and Bunnik, 1981), although reports showing experimental verification of model results are sparse. In this paper the effect of canopy architecture on the spectral response of two wheat canopies are examined. The canopies differed primarily in the geometric arrangement of their leaves, with other factors such as single leaf reflec-

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tance, green leaf area index, and total dry phytomass being essentially the same. Model results and experimental data are compared, and vegetation discrimination using spectral vegetation indices at ground level and simulated at satellite altitudes is discussed.

Experimental

Spring wheat (*Triticum aestivum* L.) was planted during mid-December, 1982 at Phoenix, Arizona. Seeds were planted at a rate of 300/m in N-S rows at 0.18 m spacing in 12 m by 25 m flood irrigation basins on an Avondale loam soil (a fine, loamy, mixed calcareous, hyperthermic, Antropic Torrifluvent). All plots received an irrigation on 4 January 1983. Subsequently a "dry" treatment was irrigated in late February and again in mid-April. The "wet" treatment received irrigations in late February, mid-March, three in April, and one in early May. Although the wet treatment received an irrigation in March, several rain events provided sufficient water that growth differences due to irrigation treatment were not observed until after heading. Differences became apparent in the latter part of the season when the dry plots senesced sooner than the wet plots.

Canopy architecture varied considerably among the cultivars, all of which were obtained from CIMMYT in Ciudad Obregon, Mexico. Of the cultivars, 'Yecora 79 was the most planophile and 'Ciano 79 the most erectophile. Data presented in this report will be limited to these two cultivars. They will subsequently be referred to simply as planophile and erectophile, except where cultivar names are necessary for clarity. The basis for this classification will be discussed in a later section.

Plant measurements

Phytomass was estimated from 12 plants of each cultivar selected at random at twice weekly intervals. All above-ground plant parts were oven-dried at 70° C for at least 48 hr. Green leaf area was measured with an optically integrating leaf area meter on a subsample of three median-sized plants selected from the phytomass sample. Green leaf area per plant was converted to leaf area index (GLAI) by multiplying by the density of plants at emergence. The raw phytomass and GLAI data were smoothed with a sliding polynomial curve fitting technique to facilitate presentation.

Field spectral reflectance

Spectral reflectance measurements were made with a Barnes Modular Multiband Radiometer (MMR)[1] having band-pass characteristics similar to the Thematic Mapper bands on Landsat-4, with the exception of an additional MMR band at 1.15 to 1.30 μm (Robinson et al., 1979). A backpack transport system was devised to suspend the radiometer off to one side and slightly above the operator's shoulder level. Access to the field plots was provided by east–west boardwalks aligned just to the north of the spectral target areas and elevated about 0.2 m above the soil surface. The measurement sequence, which required about 20 min to complete, was symmetric about 1035 h (MST), the

[1] Trade names and company names are included for the benefit of the reader and imply no endorsement of the product or company by the U. S. Department of Agriculture.

approximate local time of the Landsat-4 overpass.

Reflectance factors were calculated as the ratio of the radiometer output over a vegetation target to the output over a $BaSO_4$ reflectance panel. Panel data were obtained at the start, midpoint, and finish of each measurement sequence and a time-based linear interpolation was used to estimate panel data at the time that individual targets were measured. Factors were applied to the panel data to adjust the reflectance of $BaSO_4$ in specific wavelength intervals, and for nonlambertian properties of the panel (Robinson and Biehl, 1979; Kimes and Kirchner, 1982). Additional factors were applied to MMR bands 5, 6, and 7 to correct the output from the PbS detectors for ambient temperature sensitivity (Jackson and Robinson, 1985).

Two vegetation indices were calculated from the reflectance factor data: a ratio of band 4 (0.76–0.90 μm) and band 3 (0.63–0.69 μm) and a perpendicular vegetation index from an equation developed for the Avondale soil [PVI = 64.7(band 4) − 76.3(band 3) − 2].

Single leaf spectra

On day 82 (23 March 1983) four fully expanded upper leaves were collected from plants in each plot. The leaves were sealed in plastic bags and placed in an insulated container with ice to reduce leaf dehydration and minimize changes in reflectance properties (Daughtry and Biehl, 1984). Less than 24 hr after collection, the reflectance from the upper surface of each leaf was measured in 0.01 μm increments over the wavelength range of 0.4 to 2.4 μm using a Beckman Model UV 5240[1/] laboratory spectrophotometer. The reflectance data were later digitized and multiplied by relative response functions for each of the MMR reflective bands (Jackson, 1984), resulting in single leaf reflectance values that were comparable to the MMR measured field reflectances.

Model calculations

The Suits (1972) model was used to calculate spectral reflectance for a planophile and an erectophile wheat canopy in 0.05 μm intervals from 0.5 to 2.5 μm. The calculations were for a nadir view angle and 45° sun zenith angle. Spectral reflectance and transmittance data for wheat leaves were obtained from Tables 12 and 13 of Gausman et al. (1973). Horizontal and vertical leaf projection data were taken from LeMaster and Chance (1980). These data were adjusted to representative planophile and erectophile values by using the proportions horizontal = 2 × vertical for planophile and vertical = 2 × horizontal for erectophile as suggested by Bunnik (1978).

Results and discussion

Plant measurements

Smoothed total dry phytomass and GLAI are presented in Figs. 1 and 2. Both sets of graphs reveal differences between the two irrigation treatments, but show little difference between the two cultivars which represent planophile and erectophile forms of canopy architecture. Considering the unavoidable error involved with twice-weekly sampling of a few plants, it can be concluded that, within a given irrigation treatment, both cultivars had essentially the same phytomass and leaf area index. Subsequent dis-

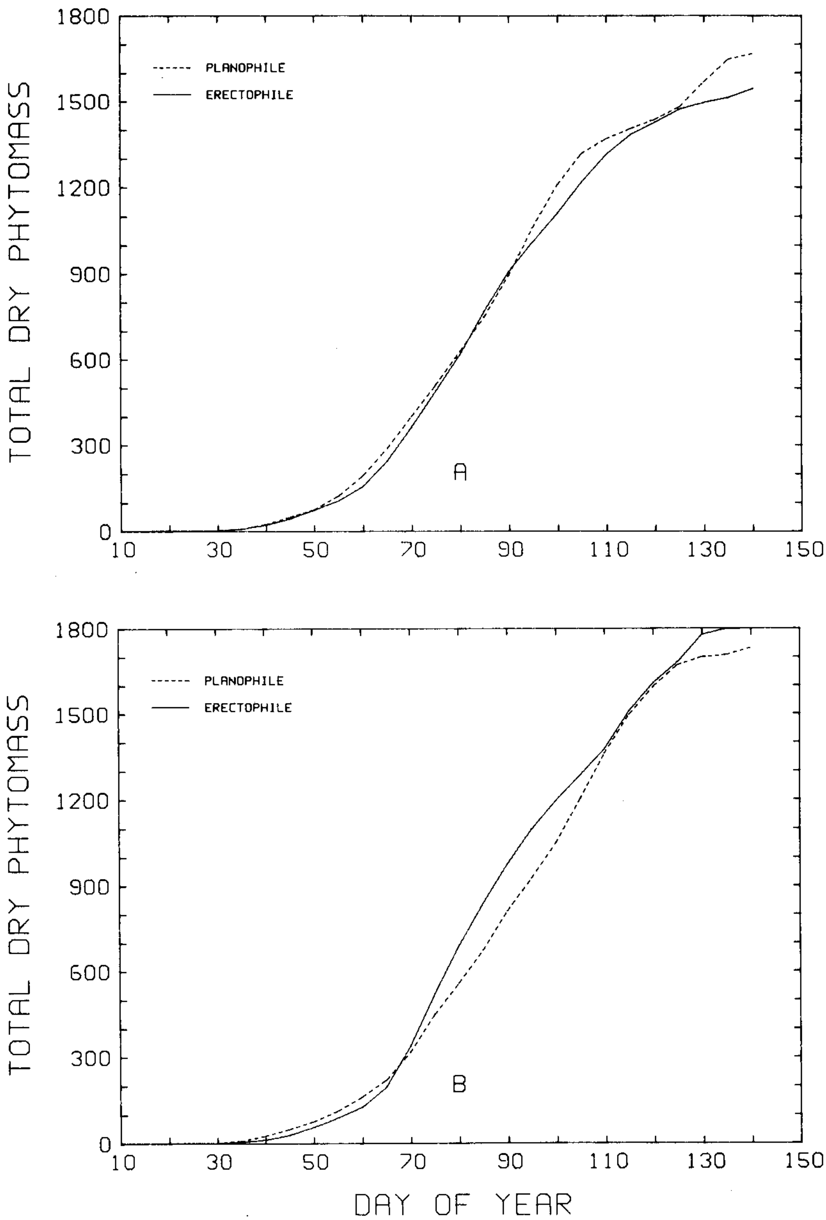

FIGURE 1. Seasonal smoothed total dry phytomass for two architecturally different cultivars and two irrigation treatments (A) dry, (B) wet.

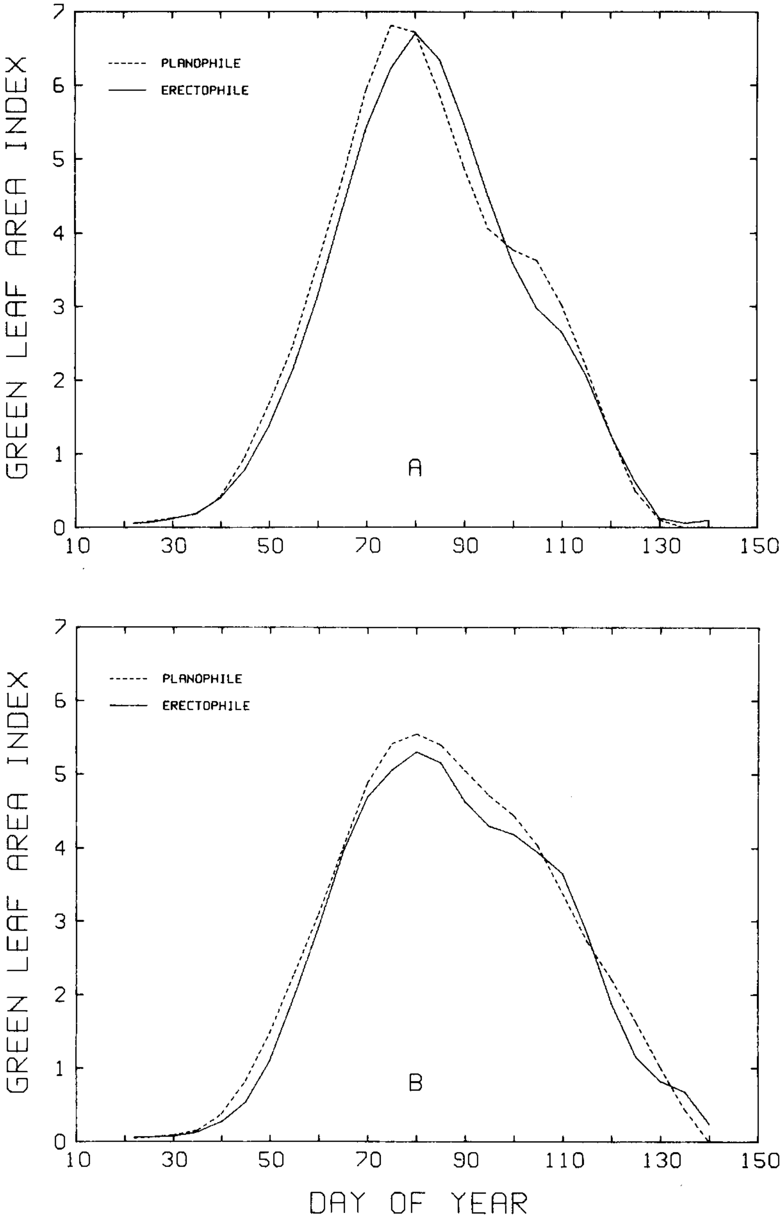

FIGURE 2. Seasonal smoothed green leaf area index for two architecturally different cultivars and two irrigation treatments (A) dry, (B) wet.

cussion of spectral measurements is based on this assumption.

Comparison of model, canopy, and leaf spectral distributions

Results of the Suits model simulation and the field reflectance factor data collected with the MMR on day 85 are shown in Figs. 3 and 4, respectively. In all wavelength intervals, the reflectance of the planophile canopy (indicated by the dashed line) was about 20% higher than the reflectance for the erectophile canopy (solid line). It is noteworthy that field measured reflectance factors (solid symbols in Fig. 4) maintain about the same difference between planophile and erectophile canopies as the model data shown in Fig. 3. Although data for only one day are shown in the figure, similar relationships between cultivars held for all measurement days. The Suits simulation data support our visual observations that the two canopies were planophile and erectophile.

Superimposing Figs. 3 and 4 shows that the measured and model data were nearly the same for the three visible bands, whereas the measured values were higher for the near-IR band (MMR 4), and somewhat lower than the model data for MMR 5, 6, and 7. The good agreement between the measured and the model data is heartening when one considers that all input data for the model were taken directly from the literature.

Also shown in Fig. 4 are reflectance factors calculated from single leaf spectra and spectral response functions of the MMR (Jackson, 1984), for day 82. The factors for single leaves were essentially the same for both cultivars, and an analysis of variance showed no statistically sig-

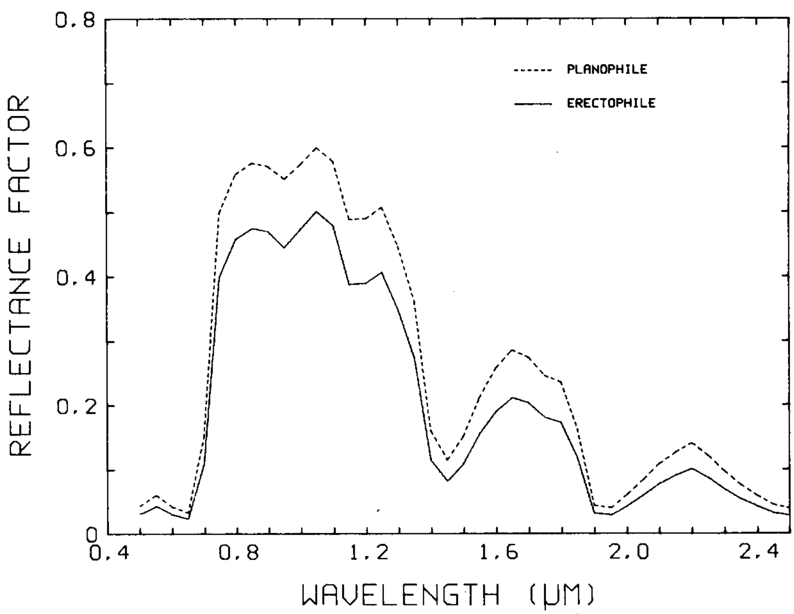

FIGURE 3. Spectral reflectance factors calculated using the Suits model for planophile and erectophile canopies (day 85).

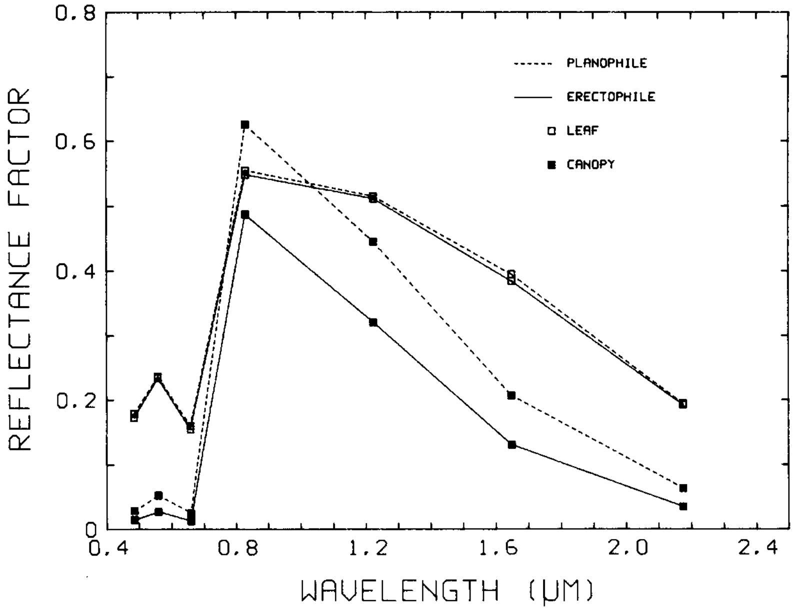

FIGURE 4. Reflectance factors in seven wavelength bands measured over a planophile and an erectophile canopy, and calculated from single leaf spectra (day 85).

nificant difference ($p = 0.05$) between them. These results support the conclusion that canopy architecture, rather than leaf reflectance characteristics per se, plays the major role in determining the spectral response of a plant canopy.

Vegetation indices

Ratios of near-IR to red reflectance factors were nearly the same for the planophile and erectophile canopies prior to day 60 (Fig. 5). After that time the ratio was considerably lower for the planophile canopy than for the erectophile canopy in the wet treatment. This difference may have resulted from unequal rates of canopy closure with the planophile canopy covering the soil more rapidly. However, the difference persisted even after 100% canopy closure. A review of photographs taken weekly of the plots revealed the rapid transition into a planophile canopy for Yecora after day 60. New leaves appeared broader and longer. Leaves near the top of the canopy flopped over presenting a planophile surface. The geometry of Ciano canopy showed very little change, remaining mostly erectophile during this period. This was also true for the dry treatment until about day 120, when the canopies were both rapidly senescing due to reduced available water. The ratio values became nearly coincident at this time, possibly due to more rapid senescence of the planophile cultivar.

In general, the PVI results were opposite to those for the IR/red ratio in that the planophile canopy had higher PVI values than the erectophile canopy from early in the season until about day 120 (Fig. 6). During the period of maximum greenness (about day 70 to 100), the vegetation indices for the two canopies differed by about 30%. However, the

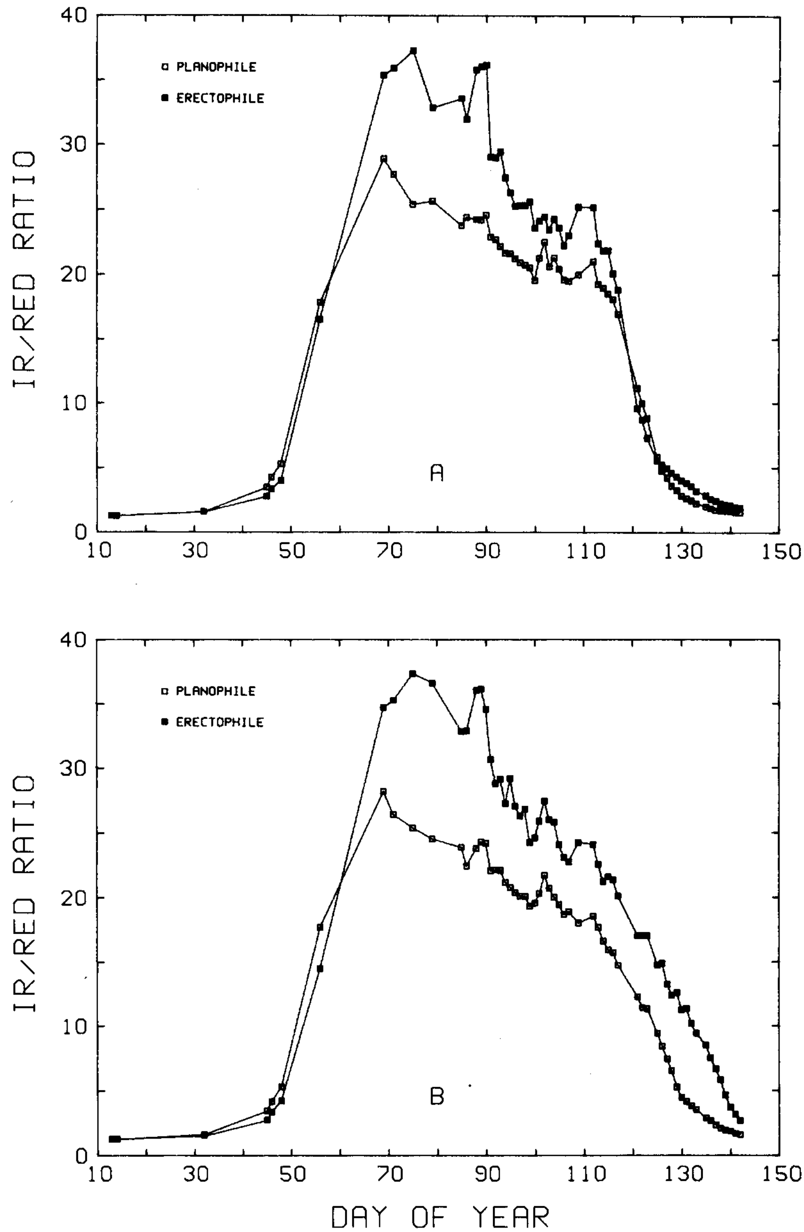

FIGURE 5. Seasonal trend of the IR/red ratio for two architecturally different cultivars and two irrigation treatments (A) dry, (B) wet.

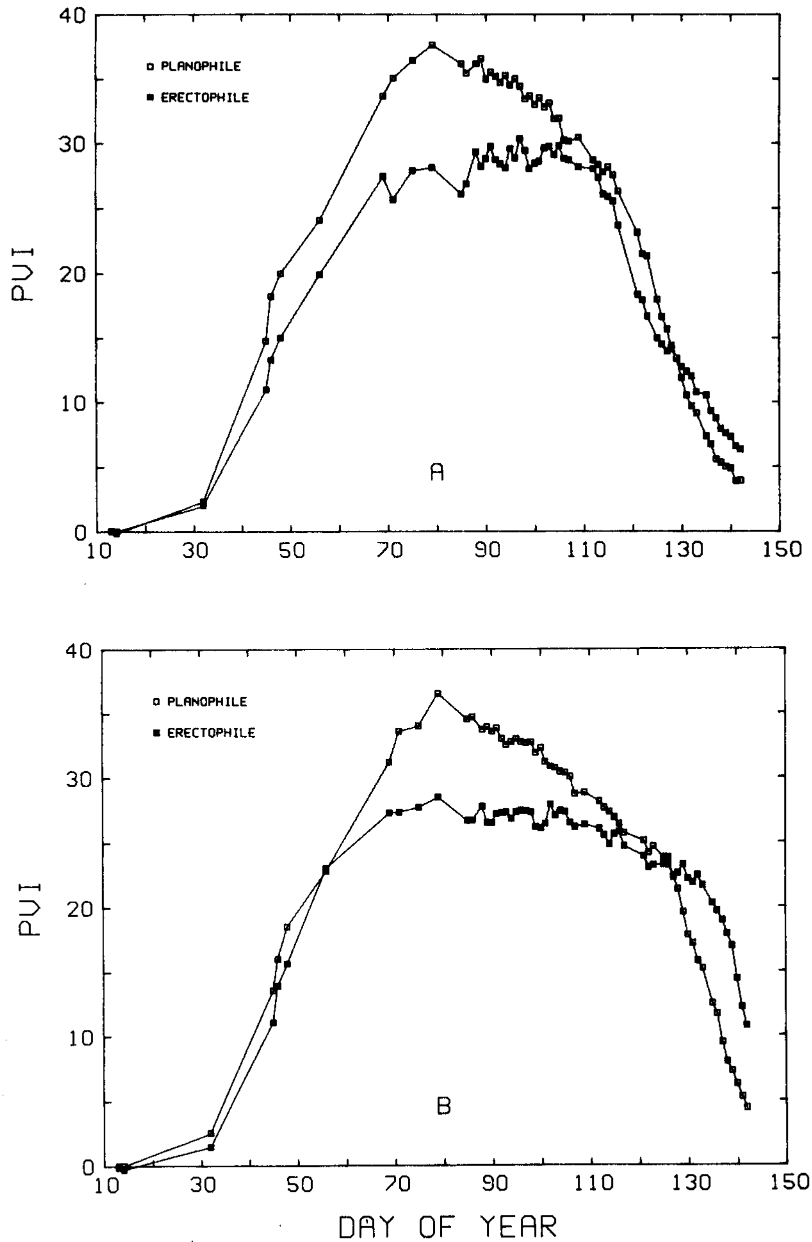

FIGURE 6. Seasonal trend of the perpendicular vegetation index for two architecturally different canopies and two irrigation treatments (A) dry, (B) wet.

order of the indices was reversed. The erectophile canopy had the highest IR/red ratio and the planophile canopy had the highest PVI. These results demonstrate that architecturally different canopies, having essentially the same phytomass and GLAI, can yield vastly different vegetation indices.

Architectural effects on vegetation indices

The vertical elements of an erectophile canopy trap reflected radiation within the canopy, with a corresponding reduction in the amount reflected vertically towards a nadir oriented radiometer. The opposite is true for a planophile canopy. The horizontal leaves reflect more in the vertical direction, and less is trapped within the canopy. As depicted in Figs. 3 and 4 and supported by the model simulations, a nadir-pointing sensor can receive 20 to 30% more radiation from a planophile than from an erectophile canopy. A change in the near-IR reflectance would cause similar changes in the IR/red ratio and the PVI. However, because the red reflectance is in the denominator of the ratio index, changes in this band can drastically affect the ratio index, but affect the PVI much less. This can be demonstrated mathematically by writing IR/red $= Y = (B4)/(B3)$, and taking the partial derivative with respect to $B4$ (which implies that $B3$ is held constant). The result is $\partial Y/\partial B4 = 1/B3$, a constant. With the PVI $= aB4 - bB3 - c$, the partial derivative, $\partial \mathrm{PVI}/\partial B4 = a$, is also a constant. However, $\partial Y/\partial B3 = -B4/(B3)^2$ and $\partial \mathrm{PVI}/\partial B3 = -b$, which shows that the change in the ratio with a change in red reflectance varies as the inverse of the square of $B3$, whereas the change in PVI with red reflectance is a constant. For green vegetation targets the red reflectance is generally low, consequently errors in its measurement, or variable atmospheric path radiance or absorbtion, can cause large errors in the ratio index, but smaller errors in the PVI.

Atmospheric effects on vegetation indices

Jackson et al. (1983) simulated atmospheric effects on various vegetation indices and demonstrated that values for both the IR/red ratio and the PVI were less than ground-measured values when viewed from space. This is because values of the red reflectance for green vegetation can, at times, be less than the atmospheric path radiance contribution to the sensor signal. However, the high values of near-IR reflectance for green vegetation are considerably less affected by path radiance. Using a procedure similar to that of Slater and Jackson (1982) and Jackson et al. (1983), the IR/red ratio and the PVI were simulated for two atmospheric conditions and one irrigation treatment (dry). The results for the IR/red ratio are shown in Fig. 7. For clear conditions (100 km meteorological range) this index is nearly the same for the two canopies. Turbid atmospheric conditions (10 km meteorological range) reduce the IR/red ratio considerably because of increased path radiance in the red band. However, it affects the ratios for the two canopies differently with the index for the planophile canopy becoming somewhat higher than for the erectophile canopy. The PVI, however is considerably less affected by the atmospheric path radiance (Fig. 8). Although the values decrease with increasing turbidity, the differences between the erectophile and the planophile canopies persist.

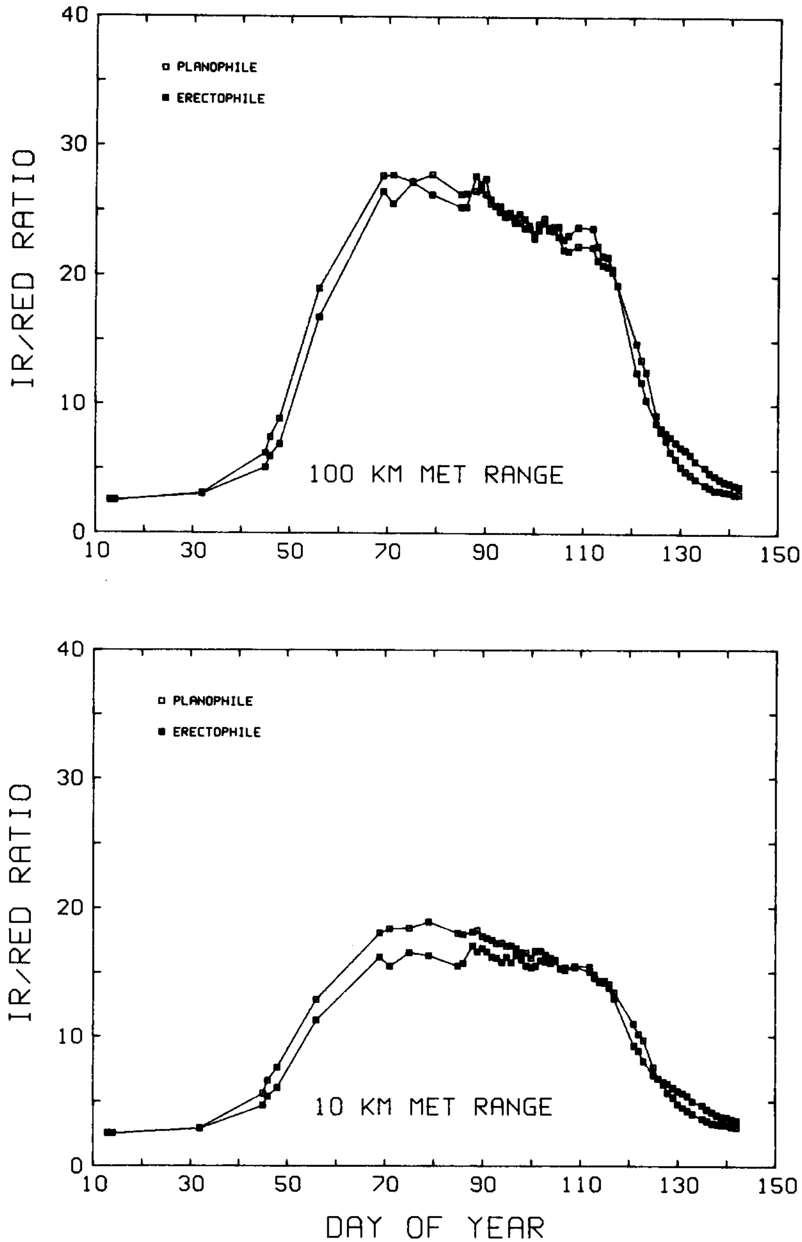

FIGURE 7. Simulated values of the IR/red ratio at the top of the atmosphere for clear (100 km) and turbid (10 km) conditions; dry irrigation treatment.

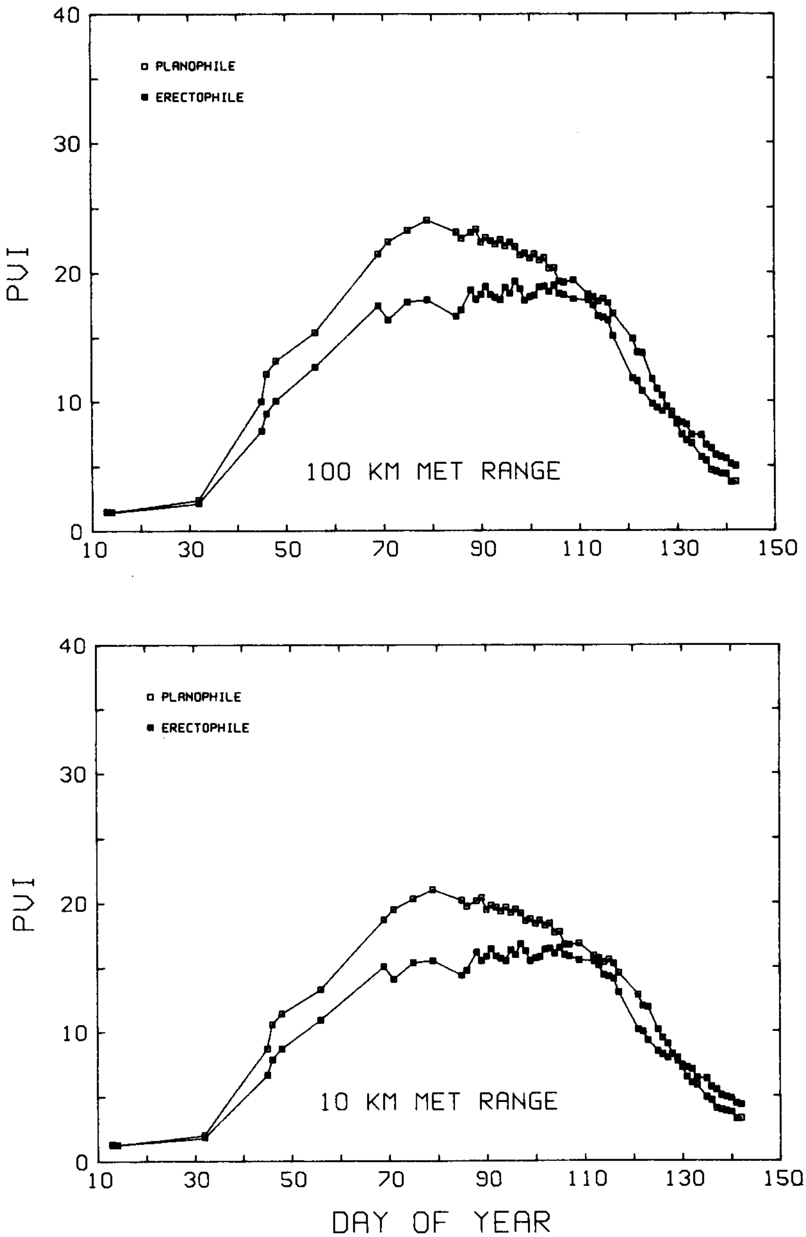

FIGURE 8. Simulated values of the perpendicular vegetation index at the top of the atmosphere for clear (100 km) and turbid (10 km) conditions; dry irrigation treatment.

Concluding Remarks

Model calculations and experimental results showed that radiation reflected in a vertical direction from plant canopies was considerably greater from planophile canopies than from erectophile canopies. The IR/red ratio was higher for the erectophile canopy, whereas an orthogonal index (PVI) was higher for the planophile canopy. These results demonstrate a limitation in the comparison of algorithms relating spectral vegetation indices that do not account for canopy architectural differences to plant properties such as green leaf area index and total dry phytomass.

For green vegetation targets the ground-measured red reflectance is generally low, and is lowest for erectophile canopies. Under these conditions, small absolute measurement errors can cause larger relative changes in the IR/red ratio than would be observed for orthogonal indices such as the PVI. Simulation studies show that the IR/red ratio is drastically affected by atmospheric path radiance. Thus, for space acquired data, values of the ratio for erectophile canopies may be greater than or less than values for planophile canopies, depending on atmospheric conditions. On the other hand, the PVI maintains the same relationship, with the planophile canopy having higher values than the erectophile canopy regardless of atmospheric conditions.

Although only data for the two-dimensional PVI are discussed in this report, calculations of four- and seven-band greenness indices showed similar results. It is evident that orthogonal green vegetation indices are superior to ratio indices for discriminating between architecturally different canopies, especially when satellite data are used. It is not evident, however, that the orthogonal index is superior to the ratio index for assessing phytomass or GLAI in canopies having the same architecture.

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